



Spectral beam splitting for efficient conversion of solar energy—A review



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ABSTRACT

Spectral beam splitting is a promising method to achieve high efficiency solar energy conversion. Its potential applications include multi-junction PV receivers, hybrid collectors and even biomass production. Although spectral splitting receivers can achieve high theoretical conversion efficiencies, they have not yet evolved to the commercial level. In this paper, we provide a review on the recently published research in this field and discuss the drawbacks associated with practical applications. Suggestions are made which we believe will lead to improvements in optical efficiency (including geometrical limitations) and the fabrication costs of spectrally splitting solar receivers.

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1. Introduction

Efficient energy harvesting from sunlight is considered to be a promising solution to the issues associated with burning fossil fuels. Burning hydrocarbons increases the concentration of greenhouse gases in the atmosphere resulting in adverse climate

change. At the same time, depletion of such non-renewable resources in nature increases their prices.

The amount of worldwide energy consumption in 2011 was about 5.48×10^8 TJ [1] which means that the average total power consumption was about 17.4 TW. In comparison, the radiation on the Earth received from the Sun is about 162,000 TW [2]. This implies that harvesting even a tiny fraction of this solar radiation can meet both the current and future energy requirements of the world.

Two main mechanisms of capturing sunlight and delivering useful energy have been developed and commercialised so far: photothermal and photovoltaic. Photothermal collectors transform

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the solar radiation into useful heat, while photovoltaic receivers (PV cells) are able to produce electricity directly from sunlight. The first reported practical conversion of solar radiation into power was carried out by Augustin Mouchot in 1878 [3]. He used a solar thermal collector including a conical reflector to run a heat engine. The first practical direct conversion of sunlight into electricity using photocells was carried out in the mid-1950s with a conversion efficiency of 6% [4]. Since then the collection and conversion mechanisms have evolved and conversion efficiencies have increased.

PV cells have now reached efficiencies as high as 43.5% [5] in laboratory measurements. However, such efficiency comes with a very high fabrication cost due to the need to manufacture multi-junction solar cells [6]. Commercially viable cells are mainly monocrystalline and multicrystalline silicon cells with module efficiencies ranging from 14 to 20%.

Utilising PV cells under concentrated solar radiation can reduce the cost of producing solar electricity [7] and also the embodied energy payback period [8] of the required devices. In this method, the majority of the PV cell area is replaced by solar concentrators such as lenses and mirrors, which are generally cheaper than PV cells. For example, the cost of a parabolic trough including the mirrors, tracking devices, and required structures costs about 295 (\$/m²) [9], whereas a utility scale photovoltaic system made of polycrystalline silicon cells (with median efficiency of 14.5% and one axis tracking) costs about 638 (\$/m²); 44% of the later is just due to the cost of the PV module [10] which is equal to about 280 (\$/m²). Assuming the concentration ratio of the parabolic trough to be 10 times (which is easily achievable), just one-tenth of the same PV cell area is required to be installed as the receiver. This means that the cost of the cell–parabolic trough combination will be 323 (\$/m²), which is almost half the price of the original system. The difference becomes more significant when high-efficiency, more expensive multi-junction cells are used as the receiver [11]. It should be noted that the cost benefit is practically achievable when the additional costs associated with using solar cells under concentrated radiation (such as the cost of cell cooling) is kept low.

An important issue associated with concentrating PV systems is that the efficiency of the cells is affected at high temperature [12]. Sufficiently high temperatures may also physically damage them. Various methods for cooling PV cells under concentrated illumination have been proposed [13] and these depend on the geometrical configuration as well. Such methods include passive (such as buoyancy induced flow) and active (such as fans, impinging water, and cooling channels) mechanisms for low and high (> 150 ×) concentration levels respectively.

In both cooling methods, the heat absorbed from the PV cells is either dissipated to the environment or delivered as additional useful energy in hybrid solar collectors [14–19]. These can be considered ‘post-absorption’ heat management solutions. Another solution for addressing the heating problem is by only exposing them to a selected spectral band in which the cells have better efficiencies. This ‘pre-absorption’ method removes the wavelengths of light that are not converted to electricity before they hit the cell, and requires spectral matching of the cells and the wavelength band.

Unlike thermal absorbers which capture the whole solar spectrum effectively, PV cells have a fixed, material dependent, spectral response. Photons with energies lower than the band gap pass through the semiconductor material and are generally absorbed (as heat) by the mounting at the back of the cell. Photons with energies higher than the band gap are absorbed by the semiconductor material; however, the excess energy is not used by conventional single-junction PV cells, and is generally dissipated as heat. Hence, wavelengths both higher and lower than the band

gap incur conversion losses, resulting in increased cell temperature. The efficiency of a PV cell consisting of a single semiconductor material with band a gap of 1.1 eV under the full solar spectrum is theoretically limited to about 30% [20].

Three different mechanisms have been suggested in the literature to alleviate the spectral mismatch problem of solar cells and increase their efficiencies. The first one is using a thermophotovoltaic device [21,22] or a luminescent concentrator [23,24] to shift the wavelengths of the incoming radiation (by absorbing and reemitting the light) towards a wavelength range which can be better matched with the cells. The second method involves monolithically stacking different semiconductors with different band gaps to create a multi-junction solar cell [25]. The third method is spectrally separating sunlight into various wavelength bands using a spectral beam splitter and directing each band to the most efficient receiver (for example a solar cell with suitable band gap). Each method has its own benefits and drawbacks.

Geometric limitations of the absorber/emitter component, optical losses, and non-ideal properties of the emitter can affect the efficiency of a thermophotovoltaic device [26]. Luminescent concentrators suffer from degradation as well as optical and re-absorption losses [27] and hence they have low efficiencies. Practical multi-junction cells have achieved efficiencies as high as 43.5% [5] but they are still too expensive to be commercialised in the mainstream PV market. Lattice matching and a few more technical issues [28,29] need to be addressed in the design and fabrication process of multi-junction cells to make them competitive for terrestrial energy applications. It should be noted that multi-junction cells also take advantage of spectral separation. However, in the current text, spectral splitting refers to lateral spectral separation of light using optical filters.

The aim of this paper is to provide an up to date review of the research outcomes (published after 2003) in the field of spectral splitting and to evaluate prospects of utilising this method in solar receivers. We investigate spectrally splitting solar receivers from the system point of view, including the optical elements (such as concentrators and waveguides), net combined efficiency, and the type of splitting system used in the configuration. Furthermore, this article will review hybrid configurations which harvest useful thermal energy.

2. Spectral splitting methods

The concept of harvesting solar energy by splitting the solar spectrum and directing each band to the most efficient convertor was suggested for the first time by Jackson [30] in 1955; however the first experimental work was demonstrated by Moon et al. [31] in 1978. This method is still used extensively to address the spectral mismatch problem of solar cells.

A thorough review on the application of spectral beam splitting for efficient harvesting of solar energy has been presented by Imenes and Mills [32]. They reviewed an extensive range of research activities in this field published up to 2003. However, because of high conversion efficiencies and increased design flexibility achieved by spectral splitting, the field has advanced considerably since then. The later advantage is due to the possibility of using more versatile types of semiconductor materials compared to monolithic multi-junction cells that constrain the design due to considerations such as lattice matching between the adjacent semiconductors.

Various mechanisms for spectral splitting of sunlight have been proposed. For example, holographic concentrators [33,34] can split sunlight into several bands along with concentrating it. This mechanism has been shown to be advantageous in low concentration solar collectors [35]. The most well-known method is using

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